

Constraining properties of black hole mimickers with gravitational wave observations of binary black holes

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LIGO and Virgo have recently observed a number of gravitational wave (GW) signals that are fully consistent with being emitted by binary black holes described by general relativity. However, there are theoretical proposals of exotic objects that can be massive and compact enough to be easily confused with black holes. Nevertheless, these objects differ from black holes in having nonzero tidal deformabilities, which can allow one to distinguish binaries containing such objects from binary black holes using GW observations. Using full Bayesian parameter estimation, we constrain the parameter space of such “black hole mimickers” with binary black hole observations from the Gravitational Wave Transient Catalog - 1 (GWTC-1).

Background

Black holes in binaries emit gravitational waves (GWs) in a characteristic *chirp* signal; the frequency and amplitude of these signals increase with time until they merge. So far, the LIGO-Virgo Collaboration has detected 10 binary black hole (BBH) events spread over two observing runs. The third observing run is currently ongoing.

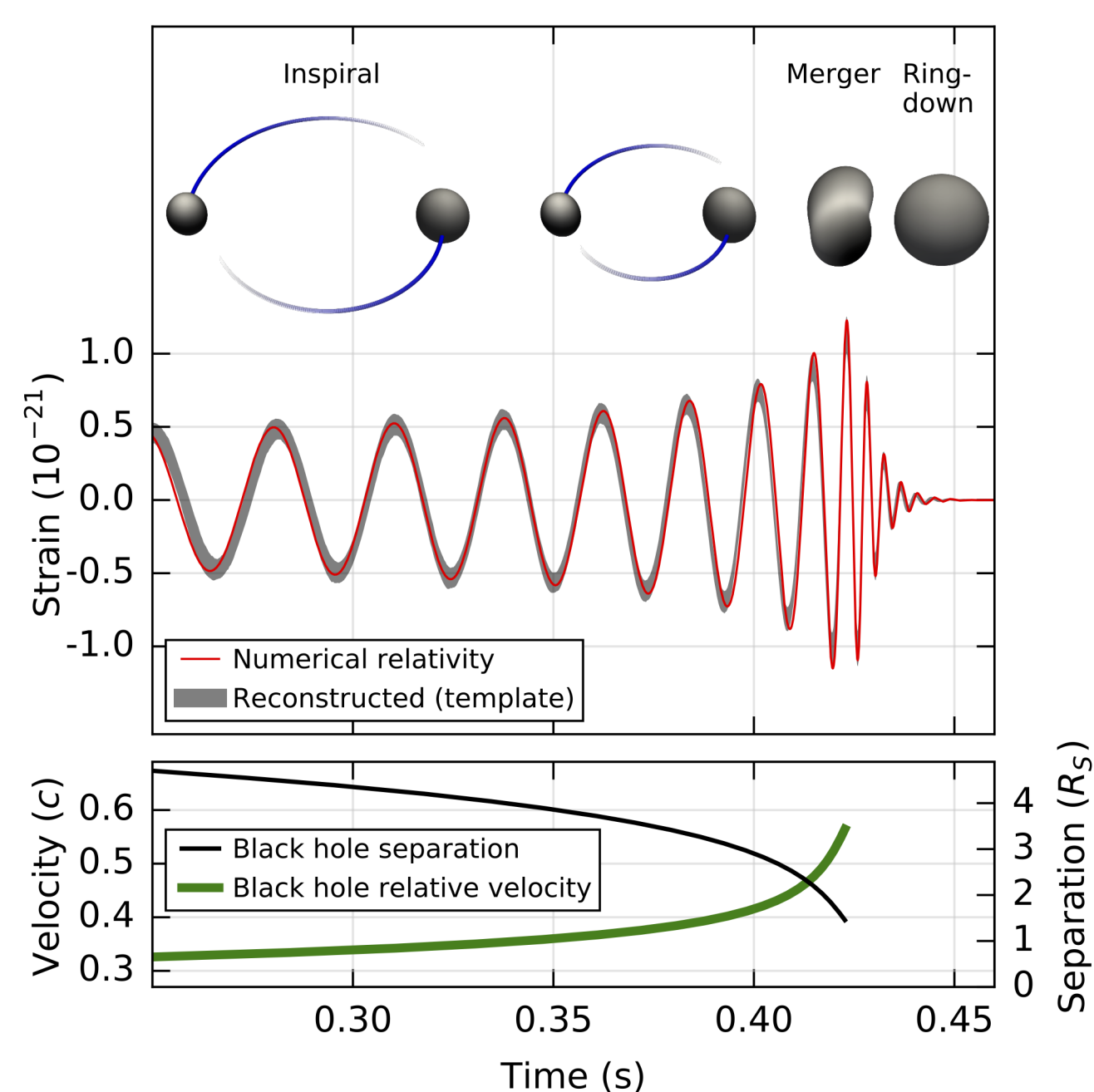


Fig. 1: Characteristic morphology of a GW signal from binary black holes. When the black holes are adequately separated in space, their speeds are slow and we can describe the system using analytical approximations; unfortunately, when they are close to each other, their speeds are really high and we have to rely on full numerical simulations to get the form of the GW signal. (Plot from the GW150914 discovery paper)

Isolated black holes in general relativity can be uniquely described by their masses and their three-dimensional spins on account of the *no-hair theorem*. Numerical simulations empirically suggest that the *no-hair theorem* should extend to BBHs, and that the dynamics should be uniquely specified using masses and spins of the two black holes.

Alternative exotic proposals to black holes like *boson stars* and *gravastars* exist in the literature. These exotic proposals are only slightly less compact as compared to black holes, but differ from black holes in that they are tidally deformed by their binary companion object. Hence, we expect these objects to have a non-zero tidal deformability parameter Λ . For an arbitrary equation of state of the exotic object, there is a theoretical, non-zero lower limit on Λ .

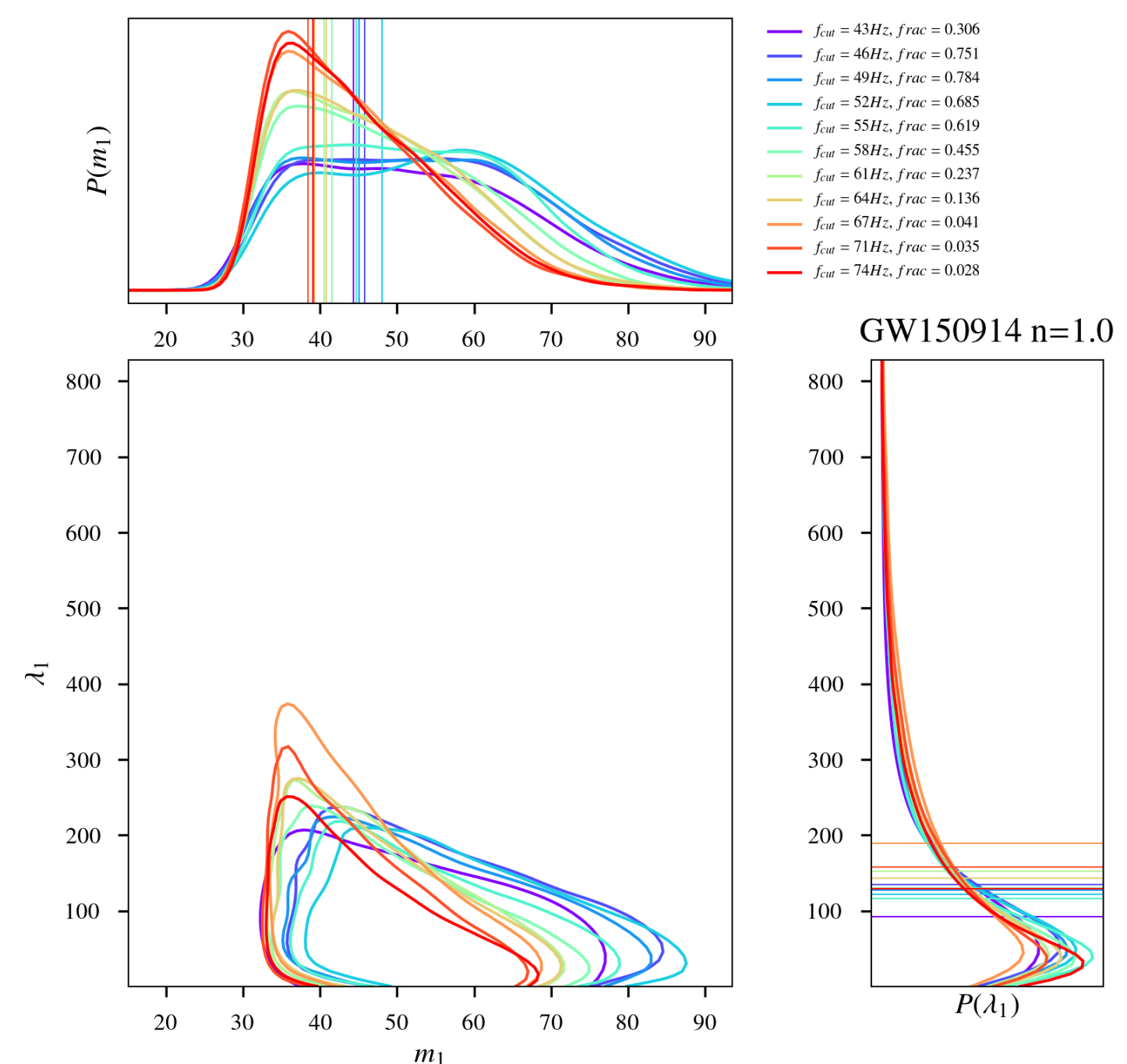


Fig. 2: Posterior (conditional) distributions of the mass m_1 and tidal deformability Λ_1 of the more massive object (marginalized over all other parameters), obtained from GW150914. The middle panel shows the 68% credible regions in the marginalized posterior distribution $P(m_1, \Lambda_1)$ while top/side panels show the marginalized one-dimensional posteriors $P(m_1)$ and $P(\Lambda_1)$. The legends show the cutoff frequencies employed in the calculation of these posteriors and the fraction of posterior samples with contact frequency (computed using $n = 1.0$) larger than the cutoff frequency employed. The vertical lines on the top panel show the 68% credible lower bounds on m_1 while the horizontal lines on the side panel show the 68% credible upper bounds on Λ_1 .

Method and Results

- Truncate the signal at certain Fourier frequencies f_{cut} before the *merger* regime. Numerical simulations of exotic objects are at a very nascent stage, and hence we cannot accurately model the signal when these objects are close.
- Estimate parameters of the GW signal considering non-spinning objects of tidal deformabilities Λ_1 and Λ_2 using Monte Carlo techniques
- Assuming perfect-fluid, non-spinning stars with a polytropic equation of state, calculate the contact frequency $f_{contact}$ for each sample in the estimated conditional distribution.
- Choose the Λ measured corresponding to the f_{cut} value that has maximum fraction of samples satisfying $f_{contact} > f_{cut}$ as the constraint. Use the measured value of Λ to rule out polytropes.

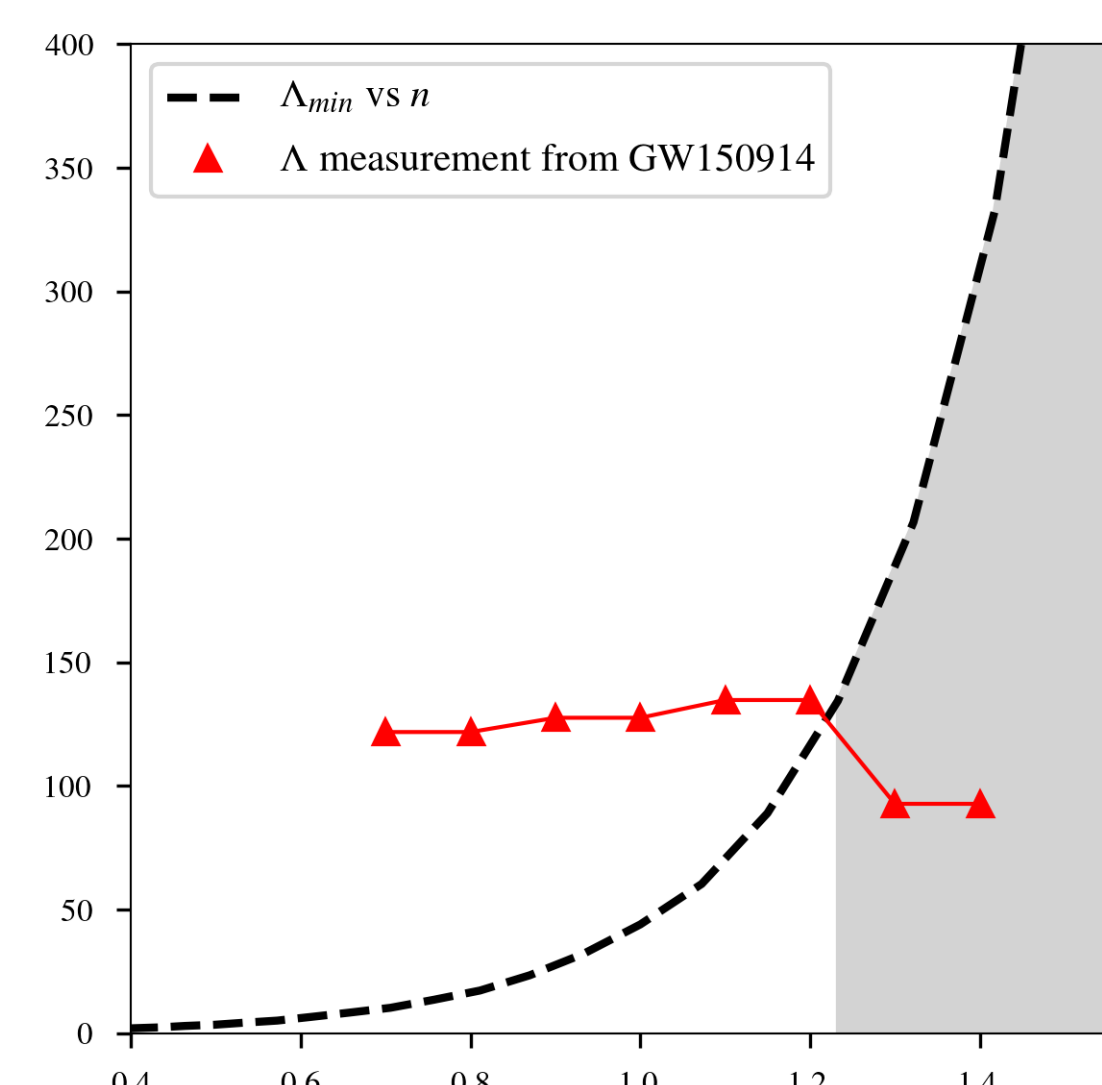


Fig. 3: The estimated Λ for various polytropic indices. The shaded region corresponds to observed $\Lambda < \Lambda_{min}$ (theoretical), and is therefore ruled out by GW150914.